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WATER MOVEMENT AND VEGETATION PATTERNS ON SHRUBLAND AND AN ABANDONED FIELD IN TWO DESERTIFICATION-THREATENED AREAS IN SPAIN

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ABSTRACT

Four large-scale rainfall simulation experiments were conducted in Spain to improve the understanding of the relationship between soil water dynamics, soil erosion and land degradation. On different shrublands and an abandoned field, hydrological characteristics were determined in relation to spatial patterns in soil, vegetation and morphology.

During the experiments on shrubland, runoff at fine scales occurred shortly after the start of the experiments. Rapid and non-uniform infiltration near vegetation clusters, related to preferential flowpaths of water, was observed. This prevented the development of runoff over distances larger than 1 metre. The surface redistribution of water was not observed on the abandoned land. Here, little vegetation structure was present and infiltration rates were high below crusts as well as stones.

We suggest that the development of spatial structures in vegetation and soil forms a positive feedback with non-uniform infiltration and increased soil water retention. The assessment of land degradation could benefit greatly from acknowledging the importance of non-uniformity in hydrological processes. Furthermore, the presented measurements indicate that in discontinuous environments runoff measurements at fine scales cannot be extrapolated directly. In these environments a scaled approach needs to be adopted emphasizing the importance of different hydrological processes at different scales.

KEY WORDS desertification; infiltration; patchy vegetation; rainfall simulation; semiarid; microtopography; matorral

INTRODUCTION

Within the Mediterranean, desertification is one of the most important impacts expected to result from changes in land-use, water resources and climate (see, for example, Fantechi and Margaris (1986) and Jeftic *et al.* (1992)). Two of the most critical biophysical properties related to land degradation processes in Mediterranean areas are soil moisture availability and soil erosion. They constrain to a large extent vegetation development, soil structure formation and soil biological activity within Mediterranean geo-ecosystems.

The local availability of soil moisture is determined by inputs from rainfall, runon from areas upslope, and local soil storage capacity (Yair and Shachak, 1987; Dunne *et al.*, 1991; Cerdà, 1995). Both runon and soil storage capacity are on the one hand affected by properties that are static with respect to land degradation, e.g. stone content, soil texture, topography. On the other hand they are affected by dynamic properties such as soil organic matter content, root content, vegetation cover, soil crust formation and soil aggregation. On

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Mediterranean hillslopes neither the static nor the dynamic properties are distributed uniformly. Many of them vary in broken bands along contour lines and in patches related to micro-topography and vegetation. Their effect on water movement on the surface and in the soil profile is very important but quantification by means of detailed field measurements has been given little attention so far.

To examine the effect of vegetation, microtopography and soil properties on runoff and infiltration, we performed rainfall simulation experiments on undisturbed plots with different cover types located on different parent materials. Results of earlier reconnaissance type experiments (Imeson *et al.*, 1993; Karssies, 1993) showed runoff to occur rapidly under simulated rainfall conditions at fine scales ($\leq$ 1 m) on comparable hillslopes. As spatial patterns often extend beyond this fine scale, large-scale rainfall simulation experiments were designed to study their effect more accurately under extreme rainfall conditions.
The objectives of the experiments were:

1. to develop and test a field experimental design executable on undisturbed surfaces using a large-scale rainfall simulator in combination with an automated system of time domain reflectometry sensors and tensiometers;
2. to study the occurrence of runoff and sediment movement on plots with different parent materials and patterns in vegetation, microtopography and soil properties, during an extreme event;
3. to examine the relationship between runoff, infiltration and microtopography, vegetation cover and soil properties on plots with different parent materials and spatial structures;
4. to determine *in situ* soil water dynamics during wetting and drying of the soil.

The experiments were performed in the Mula basin (Murcia, SE Spain) and the Záncara basin (Cuenca, central Spain) in the summer of 1992. They form part of the work carried out within the framework of two European projects, MEDALUS (Mediterranean Desertification and Landuse) and EFEDA (European Field Experiment in a Desertification-Threatened Area). Both these projects deal with desertification and land-use changes in the European Mediterranean. In the projects, field data are being gathered and state-of-the-art modelling is applied to improve the understanding of the interactions between desertification and changes in land-use and environment (Thornes and Brandt, 1996; Bolle *et al.* 1993).

FIELD SITES AND EXPERIMENTAL LAYOUT

Four experiments were carried out at two locations (El Ardal (Murcia) and Majadillas (Cuenca)), situated in two different climatic regions, with comparable types of shrublands and land-use. At the El Ardal site, a representative abandoned field and a matorral slope on limestone were selected to study the effect of large differences in vegetation cover and microtopography. At the Majadillas site one plot was selected on marl and one plot on limestone, to study the effect of difference in parent material. The size and duration of the experiments did not allow a further site selection. During site selection the shrubland sites were considered to represent geo-ecosystems with a well developed spatial structure, while the abandoned field was considered a system where spatial organization is limited.

The climatological characteristics of the two research locations show clear differences with respect

Table I. Climatological characteristics of the field sites

Site	Month	T_{avg} (°C)	T_{min} (°C)	T_{max} (°C)	Prec. (mm)	Avg. Prec (mm)
El Ardal	January	9·4	4·9	14·0	15·3	276
	July	26·6	19·0	34·1	4·0	
Majadillas	January	5·6	2·0	9·3	50·1	394
	July	24·0	16·5	31·5	12·2	

T_{avg}, mean monthly temperature; T_{min}, mean monthly minimum temperature; T_{max}, mean monthly maximum temperature; Prec., mean monthly precipitation; Avg. Prec., averaged yearly precipitation (El Ardal 1961–1990, Majadillas 1967–1993)

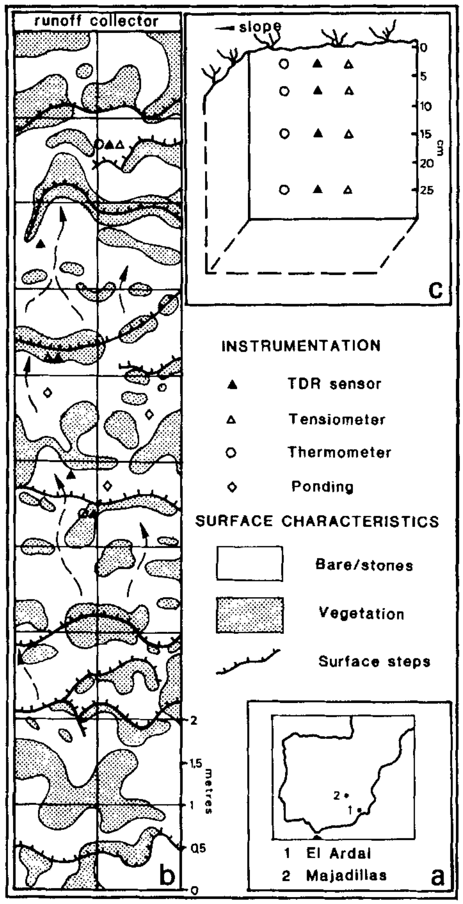

Figure 1(a). The location of the field sites (map). (b) Example of surface map experiment 3; arrows indicate observed movement of overland flow. (c) Arrangement of nest of measurement sensors in the soil within the experimental plots

to amounts of total annual rainfall and temperature regime (Table I). The average yearly rainfall at the Majadillas site is approximately 120 mm more than at El Ardal; respectively 394 mm a^{-1} and 273 mm a^{-1}. Current land-use of all the sites is grazing by small herds of sheep and goats. Their main effect is an unknown reduction of the vegetation biomass and a trampling of the soil surface around the plants, especially along grazing tracks.

El Ardal field site

The MEDALUS field site 'El Ardal' is located near Mula (Murcia province) in the upper Mula basin (Figure 1a) (López-Bermúdez *et al.*, 1991a). This part of the Mula catchment is characterized by singular hills of Eocene limestones reaching up to 600–1000 m a.s.l. They are surrounded by gently rolling lower areas, with slopes between 6 and 15 degrees, filled up with Miocene marls and more recent colluvial material.

At the El Ardal site the vegetation is characterized by a discontinuous scrub dominated by *Rosmarinus officinalis*, *Juniperus oxycedrus*, *Brachypodium retusum*, *Pinus halepensis*, *Thymus vulgaris* and *Cistus clusii*. The soil is partly covered with rock fragments of petrocalcic and limestone origin. The soil is classified as a petric calcisol (FAO, 1989) or petrocalcic xerochrept (Soil Survey Staff, 1992) and characterized by a loose, shallow, stony and gravelly, siltloam topsoil and a discontinuous and weakly developed B horizon alternating with continuous petrocalcic horizons between 25 and 40 cm depth. Below 40 cm a continuous calcic horizon is present.

Table II. Characteristics of the experimental sites

	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Site	El Ardal	El Ardal	Majadillas	Majadillas
Land type	Abandoned land	Matorral	Matorral	Matorral
Parent material	Sec. Limestone	Limestone	Marl	Limestone
Dominant vegetation	Annuals	*R. officinalis* *B. retusum*	*T. vulgaris*	*T. vulgaris* *Q. coccifera* *B. retusum*
Slope angle (deg.)	7	11·5	13·6	18
Range slope angle (deg.)	6–8	9·5–14·5	13–15	16–20
Surface characteristics (% surface cover)				
Vegetation	19·4	37·3	48·0	57·3
Brachypodium retusum	0	17·4	9·0	35·7
Annuals	19·4	3·2	10·9	3·7
Bushes*	0	16·7	27·8	16·2
Lichen	0	0	0·3	1·7
Necromass (total)	6·9	0	0	2·5
Seeds	6·9	0	0	0
Litter	0	0	0	2·5
Mineral surface (total)	73·6	62·8	52·0	40·2
Crust	9·9	0	4·9	0
Bare	4·2	15·1	5·6	4·0
Rock fragments (total)	59·5	41·7	41·5	36·2
in surface	32·8	9·7	15·4	12·7
on surface	26·7	32·0	26·1	23·5
Gavel size†	13·2 (50·8)	17·1 (9·9)	22·5 (29·8)	11·8 (39·8)
Stone size†	22·26 (52·7)	12·4 (30·6)	13·2 (43·2)	16·5 (33·3)
Boulder size†	23·7 (59·9)	18·2 (23·6)	5·8 (51·7)	7·9 (31·6)
Rock fragments in soil				
0–5 cm depth‡	59·8 (12·0)	36·8 (7·8)	35·4 (11·3)	36·4 (11·9)
10–15 cm depth‡	39·6 (6·4)	26·6 (10·4)	40·2 (8·8)	36·9 (9·6)

* Bushes contain *Rosmarinus Officinalis, Thymus vulgaris, Quercus coccifera, Juniperus* sp.
† Values in parentheses: percentage of rock fragments in surface per size fraction
‡ Values in parentheses: standard deviation of weight percentage

Majadillas field site

The EFEDA field site 'Majadillas' is located in the Záncara catchment, near Belmonte (Cuenca province), in central Spain (Figure 1a), located in a hilly region north of the major plains of La Mancha. The geology of the area is characterized by a folded structure of Jurassic and Cretaceous marls, limestones and dolomites with major footslopes and higher valley terraces of Tertiary and Pliocene age.

The Majadillas field site is located on slightly steeper slopes (13–20 degrees) than those at El Ardal. The site is covered with patchy matorral vegetation, characterized by *Thymus vulgaris*, *Brachypodium retusum*, *Quercus ilex sp. rotundifolia* and *Quercus coccifera*. The soil surface is covered with limestone and dolomite rock fragments. The soils are classified as a calcic luvisol (FAO, 1989) or typic haploxeralf (Soil Survey Staff, 1992). The soil profile on marl is characterized by a stony top layer above a B_t horizon with a high clay content. The profile on limestone has a stony top layer overlying a 40 cm thick B_t horizon. Locally more shallow soils are present on limestone, classified as petric calcisol (FAO, 1989) or petrocalcic xerochrepts (Soil Survey Staff, 1992).

Experimental layout

Plot descriptions at El Ardal. Experiment 1 was carried out on a field that had been abandoned for 10 years. The field was formerly used for growing wheat and is presently dominantly covered by annuals (19·4 per cent; see Table II for characteristics). The surface is mainly covered by rock fragments (59·5 per

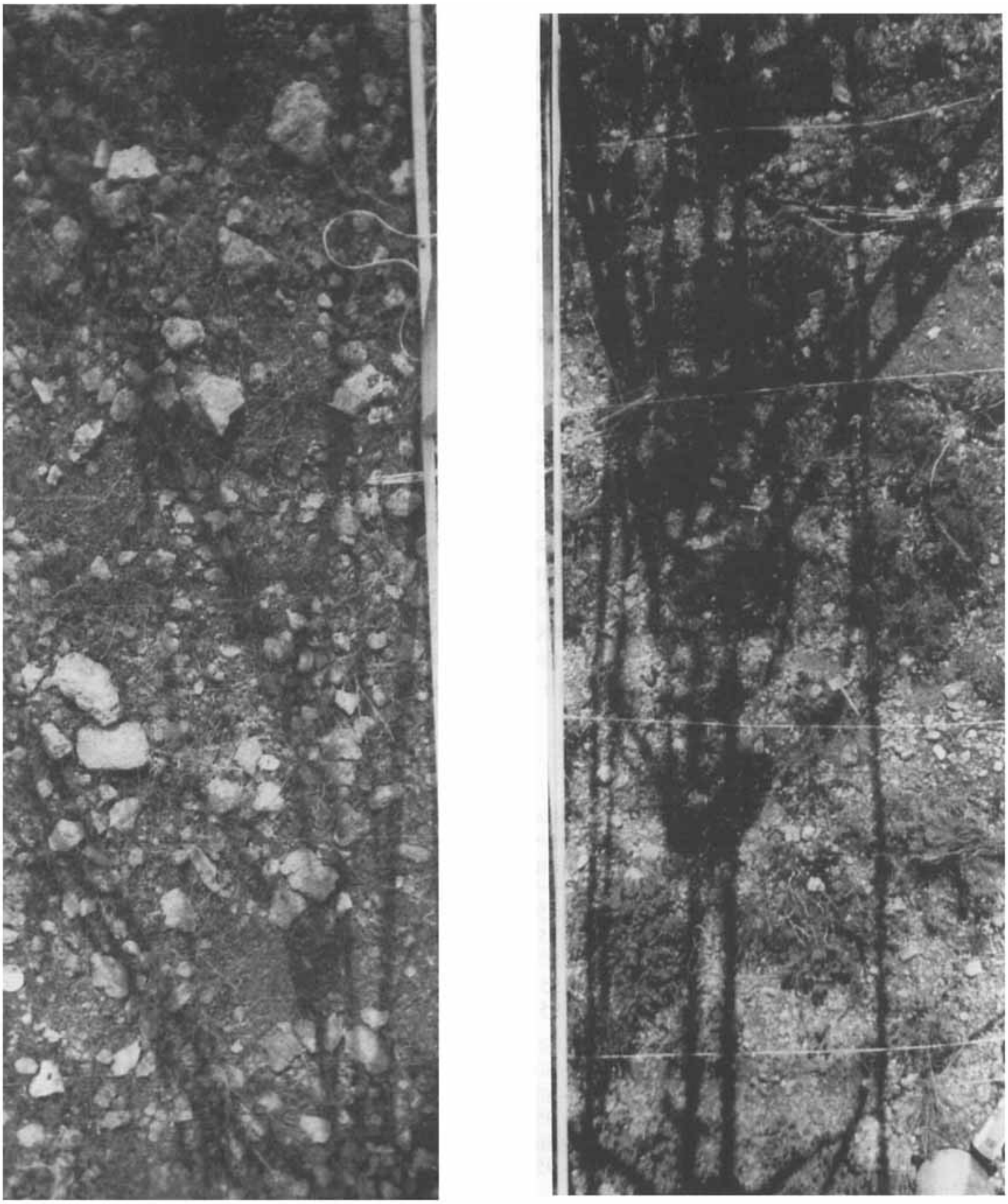

Figure 2(a). Photo of the surface of experimental plot 1. (b) Photo of the surface of experimental plot 4

cent) originating from ploughing and reworking of the petrocalcic horizon. Approximately 50 per cent of these rock fragments are embedded in the soil surface. Crusts were observed on 9·9 per cent of the plot surface. A photo of the plot of experiment 1 is given in Figure 2a. At a depth of 25 cm a calcic horizon is present extending in different layers down to 60 cm. The surface horizon contains less than 4 per cent of organic matter.

Experiment 2 was performed on a limestone hillslope covered with matorral vegetation dominated by bushes (*Rosmarinus officinalis*, 16·7 per cent) and grasses (*Brachypodium retusum*, 17·4 per cent). Both bushes

and grasses are mostly situated on the outer, often stony edges of small terracettes. The slope angle of this plot is slightly steeper than the slope angle of the plot of experiment 1 (respectively 11·5 and 7 degrees). The coverage by rock fragments is 47·7 per cent, of which approximately 20 per cent are embedded in the soil surface. Crusted surfaces were absent. At 16 cm depth a calcic horizon is present, alternating with various B horizons down to 36 cm. The A horizon contains 5·2 per cent of organic matter. An overview of soil surface characteristics can be found in Table II. Soil characteristics are summarized in Table III and are described more extensively by López-Bermúdez *et al.* (1991a, b).

Plot descriptions at Majadillas. Experiment 3 was carried out on a part of the matorral site Majadillas underlain by marls. Vegetation cover at this experimental plot is dominated by annuals (10·9 per cent) and bushes (*Thymus vulgaris*, 27·8 per cent). The bushes in particular are located at the outer, often stony rim of terracettes. Surface crusts, covering 4·9 per cent of the experimental plot, are sometimes located in between these rims. Rock fragments cover 41·5 per cent of the soil surface; 37 per cent of these rock fragments are embedded in the surface. The soil profile is characterized by a stony surface layer of 25 cm on top of a clay-rich B_t horizon. Clay content is high (36 per cent) throughout the profile. The organic matter content is below 4 per cent in the upper horizon.

Experiment 4 was performed on a part of the matorral slope underlain by limestone. The dominant vegetation on this plot consists of bushes of *Thymus vulgaris* and *Quercus coccifera* (in total 16·2 per cent) and grasses, mainly *Brachypodium retusum* (35·7 per cent). Both bushes and grasses are mainly located along terracette rims, often having a high stone content. No crusted surfaces were observed on this experimental plot. Surface cover by rock fragments was 36·2 per cent of which approximately 30 per cent were embedded in the surface. The soil profile consists of a stony A horizon, with a low clay content, overlying a less stony B_t horizon, rich in clay. At 58 cm stone content increases again up to more than 50 per cent. The organic matter content is 7·1 per cent in the upper horizon. Characteristics of experimental plots 3 and 4 can be found in Tables II and III; a photo of plot 4 is given in Figure 2b.

Table III. Soil characteristics at the experimental sites

	Horizon	Depth	% Stones	% Sand	% Silt	% Clay	% OM	% $CaCO_3$
Experiment 1	Ap	0–15	2–15	57	22	21	3·90	49
	A2	15–25	2–15	56	21	23	3·70	49
	Bk1	25–36/46	> 80	*	*	*	0·37	94
	Cmk1	36/46–50/55	> 95	*	*	*	< 1·0	94
	Cmk2	50/55–60	> 95	*	*	*	< 1·0	94
Experiment 2	Ah	0–16	15–50	32	43	25	5·20	43·6
	B11mk	16–21	> 80	*	*	*	< 1·0	> 60
	B12	21–24	> 80	–	–	–	< 1·0	> 60
	B21mk	24–32	> 95	*	*	*	< 1·0	> 60
	B22	32–36	> 80	–	–	–	< 1·0	> 60
	Cmk	> 36	> 95	*	*	*	< 1·0	> 60
Experiment 3	IAh	0–12	> 50	21	43	36	3·60	34·4
	IBtC	12–25	15–50	16	48	36	1·10	60·0
	IIBt	25–35	< 2	22	44	35	0·53	66·5
Experiment 4	IAh	0–14	> 50	51	47	2	7·10	45·5
	IBt1	14–37	15–50	28	42	30	1·80	47·8
	IBt2, ck	37–58	2–15	18	52	30	1·00	59·4
	IIBt1, cm	58–58	15–50	40	40	20	1·00	51·3
	IIBt2, cm	68–95	> 50	62	24	14	0·30	43·9

OM, Organic matter
* Not sampled
– Not available

Experimental design

During the rainfall simulation experiments, measurements were carried out on 10 m × 2 m sized plots, located with their long axis parallel to the line of gradient. To exclude flow of surface and soil water from the upper slope into the measurement area, the plots were separated from the upper slope by inserting a plate into the soil. At the downslope side of the plots a gutter was installed to collect runoff and sediment in polyethylene bottles at intervals of 2 min. Plastic sheets served as a wind shield and prevented rain falling directly into the runoff gutter.

Rainfall was simulated with a sprinkler type of simulator (Mulligen, 1990) with Tee Jet 20W nozzles (Spraying Systems Co., USA), covering an area of 20 m^2 (Figure 3). The intensity was kept at 70 mm h^{-1} and the falling height of the drops was 3·5 m. The chosen rainfall intensity and minimal duration (30 min) has a recurrence interval of approximately 15 years at the El Ardal site (based on daily totals over 30 years at the Cierva reservoir, at 4 km distance). For the Majadillas site no long-term rainfall intensity data are available. However, it is assumed that the simulated events are realistic extreme events for these hillslopes. During the experiments at El Ardal, distilled water (EC_{25} of 10 $\mu S\,cm^{-1}$), closely resembling natural rain, was used because it was suspected that the topsoil particles were susceptible to dispersion and crust formation (Bryan *et al.*, 1984). At the Majadillas site, groundwater ($EC_{25} > 700\,\mu S\,cm^{-1}$) was used, as dispersion of the topsoil particles was not expected to be important.

Types of measurements

On the experimental plots, bare patches were selected to visually monitor ponding and overland flow. The percentage of ponded surface was estimated at fixed time intervals and overland flow velocity was calculated by estimating the travel time of surface water coloured with rhodamine dye. The rainfall intensity was measured with small funnels throughout the experiments.

In each experimental plot, five patches were selected at which time domain reflectometry (TDR) probes and tensiometers were installed in the soil. On the abandoned field plot (experiment 1), three patches were selected with a high stone cover (> 75 per cent) and two with a crusted surface and fewer stones (< 20 per cent stone cover). For the other experiments two patches were selected covered by *Rosmarinus officinalis* (El Ardal) or *Thymus vulgaris* (Majadillas) and three patches with bare surface.

Each spot contained TDR probes at depths of −2·5, −7·5 and −15 cm. At three patches an additional TDR probe at −25 cm was installed. In total 18 probes were installed per experiment. The 10 cm long,

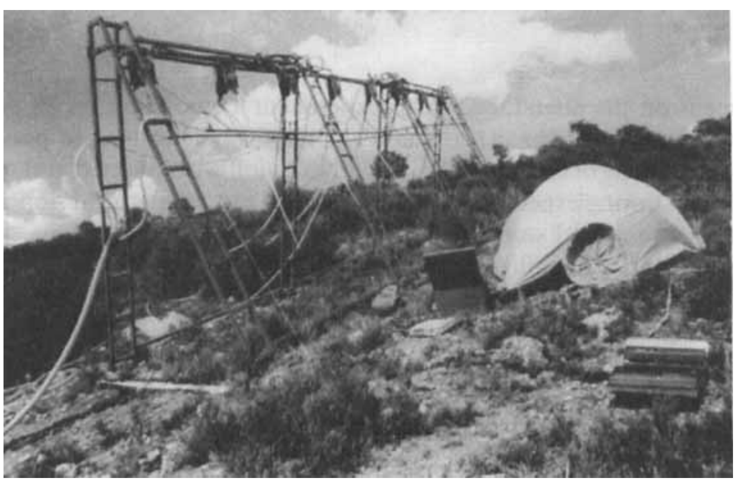

Figure 3. The rainfall simulator used during the experiment

triple-rod TDR probes were connected to an automated TDR measuring system as described by Heimovaara and Bouten (1990). With the software of this system soil moisture contents were calculated using the method given by Topp *et al.* (1980).

The system allowed the measurement of soil moisture at 2 min intervals for nine sensors, equally distributed over three patches, during the application of rainfall. For the abandoned field plot two of these three patches were located at crusted bare surfaces and one was located at a stony bare surface. For experiments 2 and 3, replicate measurements during rainfall application were made for bare surface patches together with a single measurement at a vegetation-covered patch. During the wetting phase of experiment 4, replicate measurements were made for patches covered by thyme. During the drying part of every experiment, all 18 probes were used for soil moisture measurements, as these measurements could be performed at much longer time intervals.

The influence of rock fragments in the soil on TDR measurements was seen as a major problem. The dielectric constant of stones is very different from that of soil and an often unknown amount of stones is present between the sensor poles, possibly affecting the measurements. Drungil *et al.* (1989) evaluated this problem in sandy gravelly soils, and concluded that TDR can give accurate results under these circumstances. In spite of the problems with calibration in stony soils, the main advantage of TDR remains the possibility of continuous non-destructive *in situ* measurement of soil moisture.

The most troublesome operational problem was inserting the TDR probes into the stony soil. After digging a small pit, the TDR probes were inserted horizontally in the side of the pit, perpendicular to the length axis of the plot (Figure 1c). To minimize the effects of the filled pit on the measurements, the probes were inserted laterally into the undisturbed flow area.

Tensiometers were installed in two out of five pits, at -2, $-7{\cdot}5$ and -15 cm depth, connected to a manually read tensiometer system with pressure transducers. This enabled the measurement of soil matric potential down to -500 hPa. After inserting the various sensors the pit was carefully closed horizon by horizon and covered with stones, according to maps of the original surface. The combination of *in situ* soil moisture measurements with TDR and tensiometers enables the determination of *in situ* water retention curves.

At the start of experiment 1, the soil was very wet owing to 70 mm of natural rainfall in preceding days. During the days after the first rainfall simulation, natural rainfall was recorded, prohibiting rapid drying of the soil and also causing moist initial conditions for experiment 2. Before experiments 3 and 4 were performed, at the Majadillas site, 40 mm of natural rainfall was recorded. The prevailing moist conditions did not allow the wetting front to be visually determined after the experiment. Soil wetting was therefore only determined by use of TDR sensors and tensiometers.

RESULTS AND DISCUSSION

Overland flow

During the experiment on the abandoned field (experiment 1), ponding on 80 per cent of the surface occurred 16·5 min after the start of the experiment. The relatively long time to ponding occurred despite the presence of a high percentage of crusted soil surface. No runoff was collected at the lower rim of this plot.

Rapid ponding occurred during experiments 2 and 3, carried out on matorral slopes. During both experiments, 80 per cent of the monitored surfaces was ponded within 2·5 min after the start of the experiment (Table IV). In spite of this rapid ponding and the visual observation of flow of water on the bare surfaces in between terracette rims, very little runoff and sediment were collected at the lower sides of the plots. Runoff at the bottom of these plots started respectively at 9·9 and 6·6 min after the start of the experiments, but the runoff percentage did not exceed 0·05 per cent. The sediment and runoff collected were visually observed to be related to splash and overland flow in areas near the gutter with no connection to ponded areas located further from the gutter. The sediment concentrations of the collected runoff during experiment 3 were initially high (170 g l^{-1}) and decreased to a far lower value (10 g l^{-1}). This indicates that initial dislocation of soil material by splash was important before sediment entrainment took place.

During experiment 4, 80 per cent of the monitored surfaces was ponded after 11 min. Although the

Table IV. Characteristics of soil erosion and overland flow

	Time to 80% ponding (min)	Time to wetting at −7·5 cm (min)	Time to wetting at −15 cm (min)	Overland flow velocity ($m\,s^{-1}$)	Runoff (%)	Start of runoff at gutter (min)	Maximum sediment conc. ($g\,l^{-1}$)	Sediment yield ($kg\,ha^{-1}$)	Area with overland flow (%)
Exp. 1								nil	nil
Bare	16·5	–	–	–	< 0·01	–	< 30		
Bare									
Stone									
Exp. 2								nil	15
Open	2·1	9·2	13·8	0·03	< 0·01	9·9	< 30		
Open		2·3	9·2						
Rosemary		2·3	2·3						
Exp. 3								8·81	15
Open	2·0	–	11·5	–	0·054	6·6	166		
Open		9·2	13·8						
Thyme		20·7	27·7						
Exp. 4									10
Open	11·2	7·1	43·0	0·05	0		none	–	–
Thyme		4·2	10·1						
Thyme		1·2	16·1						

Rosemary, *R. officinalis*; Thyme, *T. vulgaris*

experiment continued for 45 min, no runoff was collected at the bottom of the plot. Overland flow was observed to occur locally but not close to the gutter at the bottom of the experimental plot.

Visually observed ponding and overland flow on all matorral slopes studied, occurred long before the soil became saturated at the depth of the deepest TDR sensor (15 cm). This took between 20 and 30 min for bare patches. Addition of coloured dye during experiments 2, 3 and 4 showed all water to infiltrate at the vegetated rims of the terracettes (Figure 4). No return flow at the lower site of these terracettes was observed. At the vegetated rims of terracettes no overland flow was observed.

The lack of significant amounts of overland flow at the lower rim of the matorral plots, under the extreme conditions simulated, thus resulted from the infiltration of locally generated overland flow near scattered bushes and *B. retusum*. The local generation of overland flow before profile saturation occurs indicates that under extreme conditions Hortonian overland flow is an important process for the fine-scale ($< 1\ m^2$) redistribution of water from bare areas towards the areas covered with bushes and *B. retusum*.

The results furthermore demonstrate that for matorral slopes with a considerable vegetation structure, located on different parent materials, runoff and erosion have little significance at the plot scale ($20\ m^2$). Overland flow locally generated at the fine scale ($1\ m^2$) is rapidly buffered due to the infiltration near vegetation. These findings partly contrast with the results of earlier reconnaissance type of experiments at fine scales on the same slopes (Karssies, 1993; Imeson *et al.*, 1993). The results of these experiments, showing runoff to occur rapidly at a fine scale ($< 1\ m^2$), were confirmed here only for this fine scale. At the plot scale, however, the occurrence of overland flow and sediment transport can be considered insignificant, even under extreme event conditions.

The results of experiment 1, on the abandoned field, are in contrast with the results from the experiments at the matorral slopes. In spite of the absence of a well developed vegetation structure and the presence of crusts on 10 per cent of the surface, runoff and sediment transport were measured to be minimal on this plot. The interpretation of the results on surface and subsurface water movement on the abandoned field is only tentative at the moment. We assume that the high cover by calcic stone fragments, in combination with the presence of macropores below the stones, causes infiltration to be very rapid here and hence overland flow to be minimal.

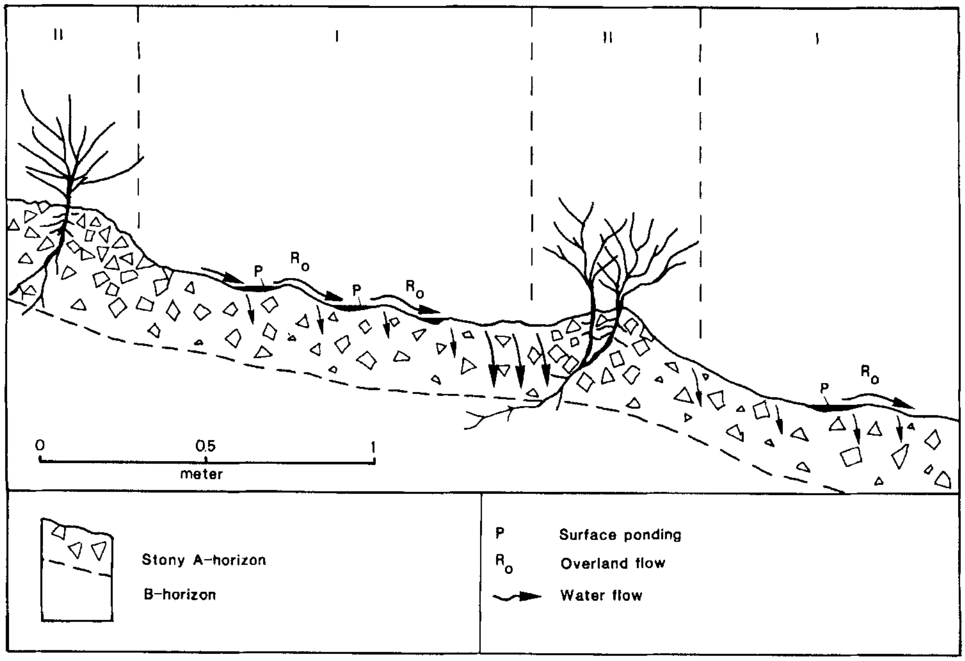

Figure 4. Cross-section and water movement on a matorral plot. Section I refers to a zone where precipitation exceeds infiltration, resulting in ponding and overland flow; in section II infiltration is larger than precipitation and runon from upslope patches

The occurrence of fine-scale surface redistribution only on sites where vegetation structures are present indicates the existence of a positive feedback between surface redistribution, non-uniform infiltration, increased water retention and the development of these structures. However, it should be noted that the importance of water redistribution to actual perennial plant growth was not ascertained during the experiments. The extension of a small part of the perennial root system far beyond the surface cover of the plants and adjacent bare patches could also indicate a more complicated situation than assumed at present.

Non-uniform infiltration

On the abandoned field (experiment 1), soil moisture below the crusted surface started to increase rapidly at shallow depths, shortly after the start of the experiment (Figure 5a). Comparison with soil moisture changes below a stony surface indicates a somewhat retarded but then more rapid wetting of deeper layers below the stony surface (Figure 5b). Unfortunately, the data for soil wetting during experiment 1 are incomplete due to malfunctioning of the equipment. Rates of soil wetting are slightly higher below stony patches (Table V).

During experiments 2 and 4, performed on matorral plots on limestone, soil moisture increased slowly below bare patches in comparison to the rapid soil moisture increase at all depths below the vegetated patches (Figures 6a,b and 8a,b). Under bare patches, soil moisture changed consecutively with depth, except for the rapid wetting during experiment 4 of the sensor located in the B_t horizon. Below vegetated patches, soil moisture increased rapidly and at almost all depths at the same time, indicating highly non-uniform infiltration due to bypass flow. Figures 8a and 8b show that at the end of experiment 4, which lasted 43 min, the soil was not entirely saturated to a depth of 25 cm. For the thyme-covered patch, saturation was already reached after 19 min (Table VI; column headed 'Time to Θ_s'). For experiment 2 saturation at -15 cm was reached in 33 min below the bare patch and in 16 min below the vegetated patch. Average rates of soil wetting were much higher during experiment 4 than during experiment 2. During experiment 4 the difference between vegetated and bare patches was much larger than during experiment 2.

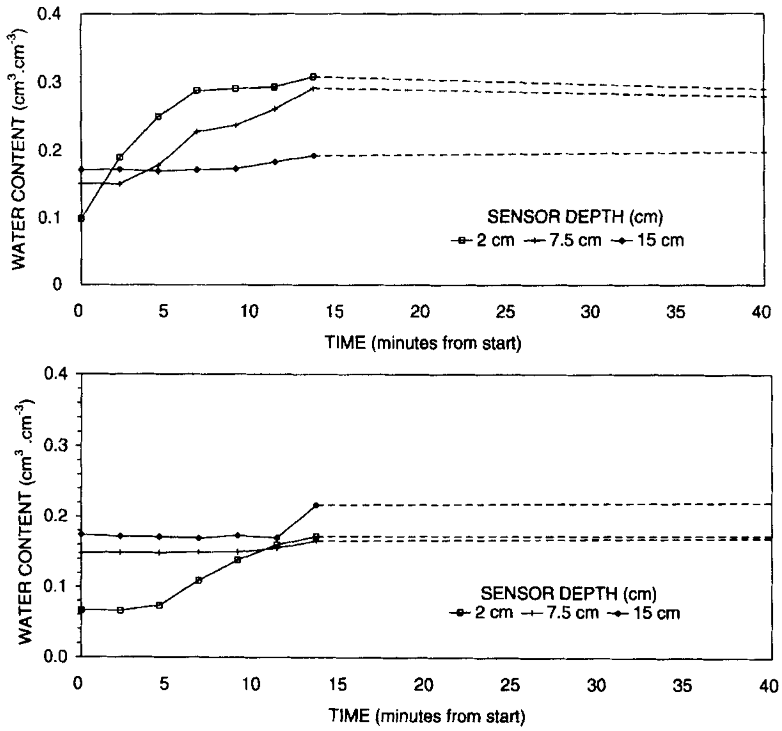

Figure 5. Experiment 1: results of TDR and tensiometric measurements. Left-hand side, bare with few stones; right-hand side, bare with high stone cover. Figures (a) and (b) reflect the change of soil moisture at different depths with time. Owing to operational errors the measurements lack the detail gained during the other experiments. Soil moisture at all depths increases rapidly shortly after the start of the experiment

The results of experiment 3, executed on the matorral plot on marl, showed a rapid increase in soil moisture below both the bare patches monitored with TDR sensors. The results of the measurements below one of these bare patches is represented in Figure 7a. The soil moisture increase below the patch covered by thyme was significantly prolonged (see Figure 7b). For both bare patches, soil moisture changed consecutively with depth, but for the vegetated patch, changes of soil moisture were irregular with depth (Figure 7b). In contrast to the results of the experiments on limestone, saturation below bare patches was reached more rapidly than below vegetated patches during this experiment. The range of average rate of soil wetting

Table V. Soil moisture content at various suctions, experiment

Experiment Number	Group	Depth (cm)	Θ_i f (m^3m^{-3})	Θ_s l (m^3m^{-3})	$\Theta_{(1)}$ l (m^3m^{-3})	$\Theta_{(2)}$ l (m^3m^{-3})	$\Theta_{(3)}$ l (m^3m^{-3})	$\Theta_{(4\cdot2)}$ l (m^3m^{-3})	WR f ($mm\,h^{-1}$)
1	Open (2)	2	0·10	0·59	0·38	0·32	0·20	0·15	25·4
		8	0·15	–	–	–	–	–	0·7
		15	0·17	0·54	0·38	0·32	0·26	0·15	2·3
	Stony (3)	2	0·06	0·61	0·51	0·44	0·26	0·19	46·1
		8	0·15	–	–	–	–	–	37·1
		15	0·17	0·58	0·37	0·33	0·22	0·15	1·6

f, field data; l, laboratory data; Θ_i, initial field moisture content; Θ_s, moisture content at saturation; $\Theta_{(1)}$, moisture content at suction of 0·1 m (pF = 1); $\Theta_{(2)}$, moisture content at suction of 1 m (pF = 2); $\Theta_{(3)}$, moisture content at suction of 10 m (pF = 3); $\Theta_{(4\cdot2)}$, moisture content at suction of 160 m (pF = 4·2); WR, averaged rate of soil wetting during experiment; –, not available

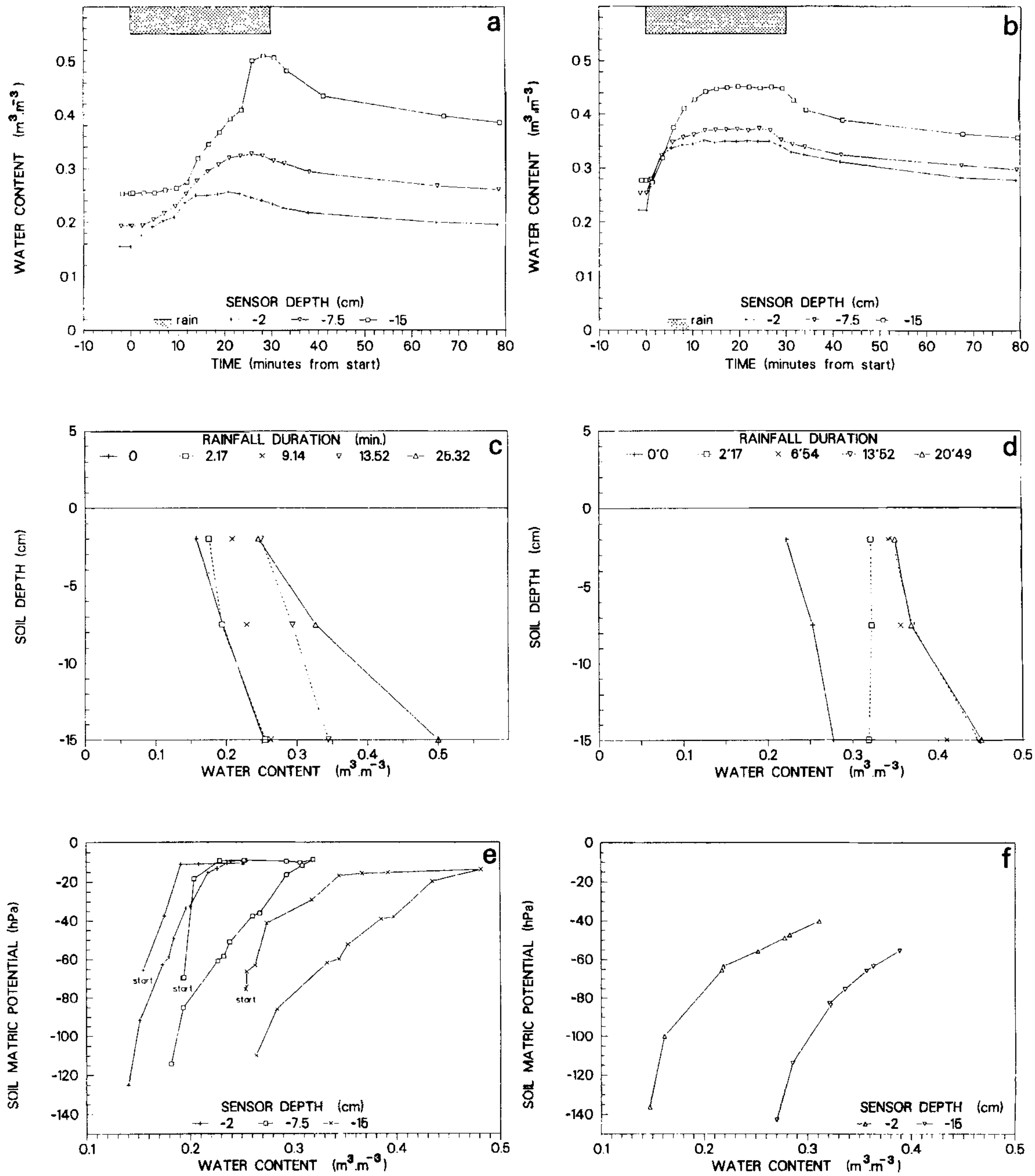

Figure 6. Experiment 2: results of TDR and tensiometric measurements. Left-hand side, bare; right-hand side, vegetaged. Figures (a) and (b) reflect the change of soil moisture at different depths with time. Figures (c) and (d) show profiles of water content during the experiment. Figures (e) and (f) give the *in situ* water retention characteristics for pF < 2·1

for bare patches was comparable with that for the vegetated patch (respectively 11·1–45·1 and 27·6–44·7 mm hr^{-1}; Table VI).

The variable and rapid soil wetting under vegetation on the matorral plots and on both stony and crusted surfaces on the abandoned field revealed the discontinuous characteristics of infiltration below these surface types. During small-scale rainfall simulation experiments (< 1 m^2) on similar types of soil, Imeson *et al.*

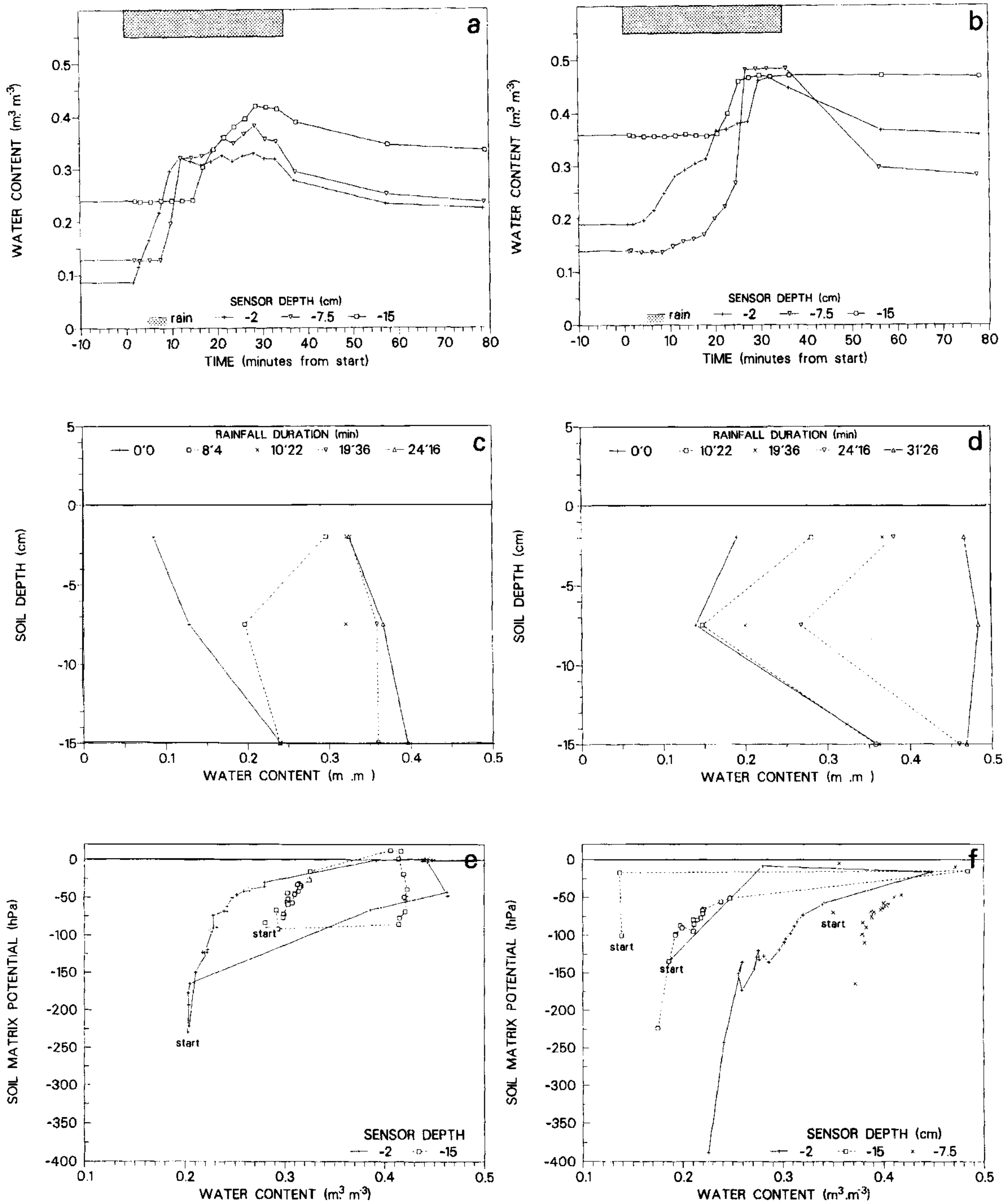

Figure 7. Experiment 3: results of TDR and tensiometric measurements. Left-hand side, bare; right-hand side, vegetated. Figures (a) and (b) reflect the change of soil moisture at different depths with time. Figures (c) and (d) show profiles of water content during the experiment. Figures (e) and (f) give the *in situ* water retention characteristics for pF < 2·1

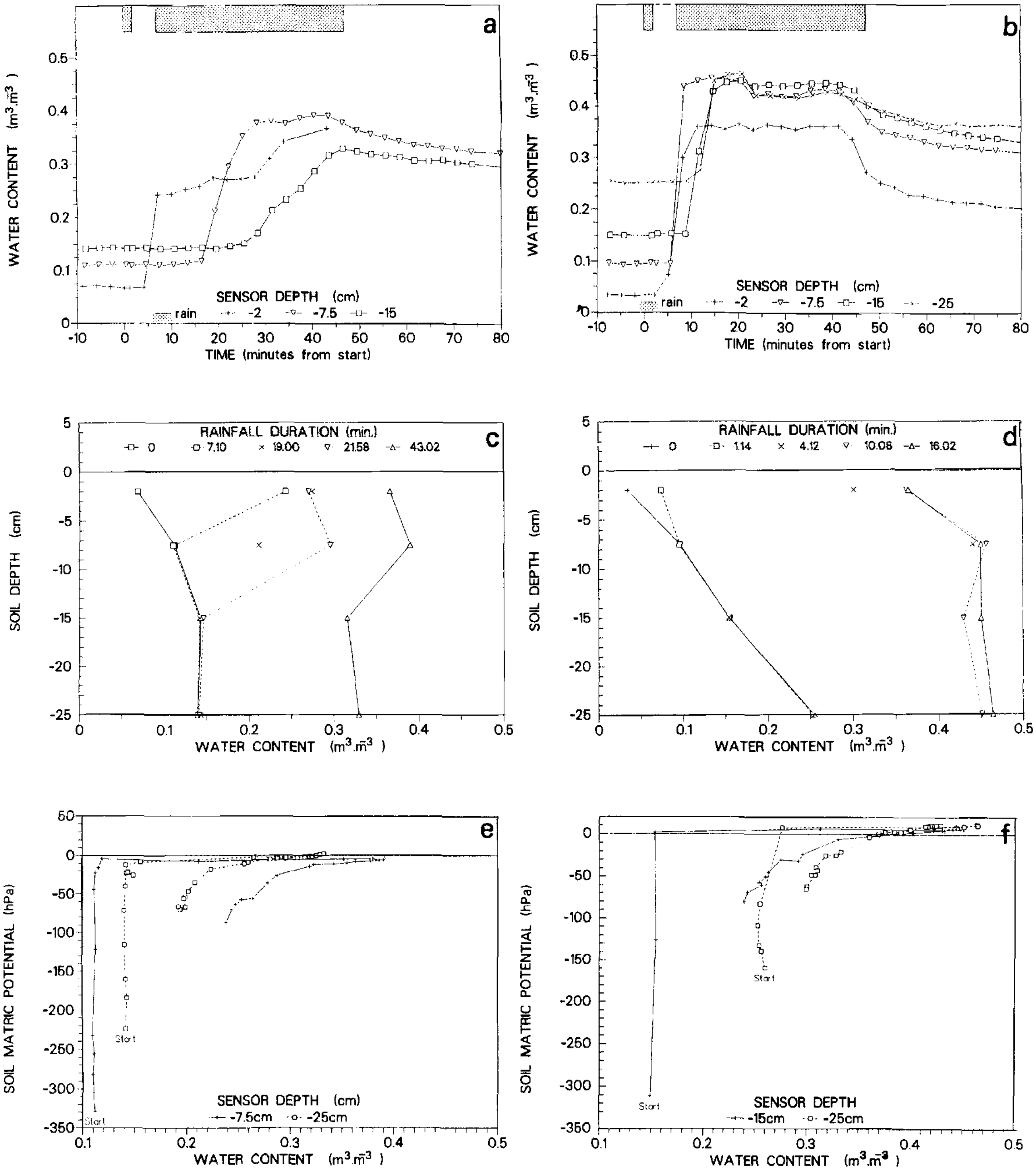

Figure 8. Experiment 4: results of TDR and tensiometric measurements. Left-hand side, bare; right-hand side, vegetated. Figures (a) and (b) reflect the change of soil moisture at different depths with time. Figures (c) and (d) show profiles of water content during the experiment. Figures (e) and (f) give the *in situ* water retention characteristics for pF < 2·1

(1992) and Cerdà (1995) showed clear pockets of wetted soil to protrude into dry soil, and hence infiltration to be very heterogeneous. The results indicate that preferential flow of water occurs under these types of surfaces and that leakage to the subsoil is important.

The average rate of soil wetting on the abandoned field plot did not show extreme differences between a crusted surface and a stony surface. However, for the soils on limestone under matorral, a major difference in

Table VI. Soil moisture content at various suctions, experiments 2, 3 and 4. See Table V for legend

Exp. number		Group unit	Depth f (cm)	Θ_i f (m^3m^{-3})	Θ_s f (min)	Time to Θ_s l (m^3m^{-3})	Θ_s fw (m^3m^{-3})	$\Theta_{(1)}$ fd (m^3m^{-3})	$\Theta_{(1)}$ ld (m^3m^{-3})	$\Theta_{(1)}$ fw (m^3m^{-3})	$\Theta_{(2)}$ fd (m^3m^{-3})	$\Theta_{(2)}$ ld (m^3m^{-3})	$\Theta_{(2)}$ ld (m^3m^{-3})	$\Theta_{(3)}$ ld (m^3m^{-3})	$\Theta_{(4\cdot2)}$ l (m^3m^{-3})	WR f ($mm\ h^{-1}$)
2	Bare	(1)	2	0·15	20·8	0·25	0·54	0·26	0·19	0·43	0·15	–	0·36	0·24	0·20	14·5
	Bare	(1)	8	0·19	21·0	0·32	–	0·32	0·23	–	0·19	–	–	–	–	15·7
	Bare	(1)	15	0·25	33·0	0·48	0·57	0·48	0·34	0·45	0·26	–	0·35	0·25	0·19	58·8
	Rosemary	(2)	2	0·26	12·0	0·33	0·60	–	–	0·38	0·16	–	0·30	0·26	0·20	12·1
	Rosemary	(2)	15	0·27	16·0	0·46	0·68	–	–	0·51	0·30	–	0·42	0·22	0·13	41·7
3	Bare	(1)	2	0·20	21·5	0·45	0·46	0·43	0·36	0·44	0·32	0·22	0·27	–	0·11	11·1
	Bare	(1)	15	0·28	32·5	0·41	0·40	0·41	0·35	0·42	0·28	0·29	0·29	–	–	45.1
	Thyme	(2)	2	0·19	36·6	0·45	–	0·32	0·31	–	0·21	0·31	–	–	–	27·6
	Thyme	(2)	7·5	0·36	36·6	0·47	0·42	–	0·49	0·29	0·36	0·39	0·25	0·14	0·10	44·7
	Thyme	(2)	15	0·14	36·6	0·48	0·37	0·15	0·48	0·30	0·14	0·18	0·23	0·24	0·15	36·6
4	Bare	(1)	7·5	0·11	40·0	0·39	0·43	0·12	0·35	0·41	0·11	0·23	0·23	0·18	0·11	41·5
	Bare	(1)	25	0·14	40·0	0·33	–	0·15	0·26	–	0·14	0·21	–	–	–	63·7
	Thyme	(2)	15	0.15	19·0	0·45	0·44	0·15	0·32	0·32	0·15	0·22	0·28	0·16	0·13	280·7
	Thyme	(2)	25	0·25	19·0	0·46	0·45	0·27	0·35	0·36	0·25	0·28	0·32	0·17	0·16	281·6

d, drying curve; w, wetting curve

soil wetting rates between bare and stony, vegetated patches was observed (Table VI). In spite of the influence of interception by *Thymus* spp. and *Brachypodium* spp., the soil was wetted more rapidly below vegetation. The rapid soil wetting near vegetation is thought to occur due to, on the one hand, local surface and soil profile conditions and, on the other hand, runon from adjacent bare areas.

The local soil profile conditions affecting infiltration are the existence of macropores, a higher stone content reducing total storage volume and an absence of soil surface slaking below the vegetation due to a higher stability of soil aggregates (Imeson *et al.*, 1993). Rapid infiltration is also possible along the roots of the bushes and through former root channels.

The runon from adjacent areas is often considered to be strongly influenced by the degree of stone cover and the position of the stones in or on the soil surface. Poesen and Ingelmo-Sanchez (1992) concluded that the effects from stones can either result in an increase in infiltration or alternatively an increase in overland flow. On the matorral slope on limestone, the high infiltration near stones is strongly affected by the profile conditions of these mostly vegetated patches. Direct physical effects of the stones as described by Poesen and Ingelmo-Sanchez (1992) are thought to be of minor importance here.

In the case of the abandoned land presented here, a direct effect of the stone cover and the position of the stones to runon could not be demonstrated. Infiltration below stones and crusts was high enough to prevent surface redistribution from occurring.

For the matorral plot on marl, a somewhat different situation exists. Here, clay content is high throughout the profile and surface conditions between bare and vegetated patches did not differ significantly. In particular, the poor cover of *Brachypodium* spp. on the vegetated patches and the presence of fewer macropores are considered important causes for the small difference in infiltration between bare and vegetated patches on marl. Therefore, on the marl plot, the vegetation is considered to be much less in control of buffering runoff from adjacent areas by means of infiltration.

Soil wetting and drying

The relationship between soil matric potential and soil moisture content was found to be different for the wetting and drying phases of experiments 2, 3 and 4. Figures 6e, 6f, 7e, 7f, 8e and 8f all clearly show this difference. Unfortunately, water retention field data are not available for experiment 1, owing to the malfunctioning of the equipment. Generally, the drying parts of the *in situ* water retention curves show correspondence to those from curves determined in the laboratory (Table VI) when adjusted for the stoniness of the soil. Especially with respect to experiments with stony soils, the application of *in situ* measurements with TDR and tensiometers proved to be favourable to the classic sampling and laboratory determination of water retention curves.

Most field data revealed lower moisture contents relative to matric potentials during the wetting phase in comparison to those during the drying phase. The difference between the two phases can amount to up to $0{\cdot}12\,m^3\,m^{-3}$ for a given soil matric potential. Furthermore, during experiments 2 and 4 on the matorral plots an extremely rapid increase of the soil matric potential was observed shortly after the start of the experiments. This rapid increase was associated with only a little change in soil moisture contents.

The discrepancies found between soil wetting and drying can be explained mainly in two ways. The first, most obvious explanation is by means of soil water hysteresis. A second explanation can be the influence of flow through macropores that are tapped by the tensiometers. If tapped, the tensiometers will reflect the high water potential existing in the macropore instead of the lower water potential still existing in the nearby soil matrix. The measurements with the TDR sensors, on the other hand, are much less affected by macropore wetting. Besides, TDR sensors reflect a mean soil moisture content of a cylinder of *c*. $70\,cm^3$ (diameter 3 cm), whereas tensiometers have much smaller diameter (0·5 cm). We think that both explanations are realistic and valid.

The results indicate the importance of soil water dynamics during the wetting phase. As normally only the drying limbs of soil water retention curves are used in soil water modelling, the differences presented can result in considerable errors when overlooked. Furthermore, the initial soil moisture conditions and the characteristics of the rainfall event will strongly affect the characteristics of the realized soil wetting. This severely complicates the understanding of the processes of infiltration, soil water retention and soil erosion.

The dynamic non-linear behaviour of soil and soil surface characteristics as affected by soil water hysteresis, initial soil wetness, slaking and dispersion, form a generally neglected but major problem for the modelling of these processes. Rainfall events of relatively short duration and with high intensity, common in Mediterranean environments, are particularly problematic in this respect.

CONCLUSIONS

Methodology

The use of the techniques, as combined here under semicontrolled conditions, provide important and new data on the behaviour of dynamic soil properties. During and after the experiments it became clear that soil stoniness needs further examination in relation to the use of the TDR technique. In practice this means that if one is interested in the moisture content of the soil matrix, the soil volume around the TDR probes should be sampled and analysed after the experiment. This can be rather complicated in very stony soils. The inhomogeneous distribution of stones in the soils restricts the use of averaged values of stone content for corrections of the TDR measurements in this respect.

Runoff and infiltration

On matorral slopes as examined in this study, covered with a significant vegetation structure, runoff is not likely to occur under extreme rainfall conditions at scales broader than 1 m. Especially on limestone soils, the rapid infiltration near bushes and grasses on stony rims of terracettes provides a buffer for the generation of runoff at the broader scale. On the matorral slope on marl this buffering seems to be less prominently developed. On the abandoned plot the lack of runoff is attributed mainly to infiltration along macropores that are not directly related to surface properties as stone cover and crusts. However, the limited amount of data does not allow further interpretation regarding land abandonment and surface response to rainfall. More research is presently being carried out on fields with a sequence of abandonment ages in order to quantify in more detail the development of spatial patterns and their effect on hydrological response.

The occurrence of water redistribution on matorral slopes, which is closely related to vegetation patterns, and the absence of this surface redistribution and vegetation structure on the abandoned field is of specific importance. We suggest that the development of spatial structures in microtopography, soils and vegetation on Mediterranean seminatural slopes forms an important positive feedback with a heterogeneous surface and subsurface hydrology.

As situations are often as complex as discussed here, we want to stress that to improve our understanding of biophysical aspects of desertification in the Mediterranean, the importance of the non-uniformity of hydrological processes, induced by spatial structures, and the existence of feedback mechanisms should be more widely acknowledged. The assessment of land degradation could benefit greatly from an increased awareness of the importance of this non-uniformity in hydrological processes.

Geomorphological implications

The measurements presented here indicate that field experiments conducted at fine scales, on the type of slopes investigated here, cannot be extrapolated directly to broader scales. The rapid infiltration of locally generated overland flow near spatial structures in vegetation and stones prevents runoff generation at the plot scale. Therefore care should be taken with using runoff measurements from fine scales as input for erosion models with a much broader scale. The measured non-linear behaviour of soil water dynamics further restricts the applicability of most existing soil hydrological and erosion models. Unpredictable initial conditions can determine to a large extent the actual infiltration and overland flow at fine scales.

Measured patterns of infiltration and overland flow indicate that the scale of observation severely influences the understanding of operating processes. Therefore we think that in areas where a close link between vegetation development and morphology is present, a scaled approach needs to be adopted (Kirkby *et al.*, 1996; Bergkamp, 1996). The approach should focus on the significance of properties and processes at

different scales. Research is presently being carried out within the MEDALUS framework to further develop such a scaled approach and to test its applicability.

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